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A galaxy rapidly forming stars 700 million years after the Big Bang at redshift 7.51

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Of several dozen galaxies observed spectroscopically that are candidates for having a redshift (z) in excess of seven, only five have had their redshifts confirmed via Lyman α emission, at $z = 7.008$, 7.045, 7.109, 7.213 and 7.215 (refs 1–4). The small fraction of confirmed galaxies may indicate that the neutral fraction in the intergalactic medium rises quickly at $z > 6.5$, given that Lyman α is resonantly scattered by neutral gas[3,5–8]. The small samples and limited depth of previous observations, however, makes these conclusions tentative. Here we report a deep near-infrared spectroscopic survey of 43 photometrically-selected galaxies with $z > 6.5$. We detect a near-infrared emission line from only a single galaxy, confirming that some process is making Lyman α difficult to detect. The detected emission line at a wavelength of 1.0343 micrometres is likely to be Lyman α emission, placing this galaxy at a redshift $z = 7.51$, an epoch 700 million years after the Big Bang. This galaxy's colours are consistent with significant metal content, implying that galaxies become enriched rapidly. We calculate a surprisingly high star-formation rate of about 330 solar masses per year, which is more than a factor of 100 greater than that seen in the Milky Way. Such a galaxy is unexpected in a survey of our size[9], suggesting that the early Universe may harbour a larger number of intense sites of star formation than expected.

We obtained near-infrared (NIR) spectroscopy of galaxies originally discovered in the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS)[10,11] with the newly commissioned NIR spectrograph MOSFIRE[12] on the Keck I 10-m telescope. From a parent sample of over 100 galaxy candidates at $z > 7$ in the GOODS-North field selected via their Hubble Space Telescope (HST) colours through the photometric redshift technique[13–16], we observed 43 candidate high-redshift galaxies over two MOSFIRE pointings with exposure times of 5.6 and 4.5 h, respectively. Our observations covered Lyman α (Lyα) emission at redshifts of 7.0–8.2. We visually inspected the reduced data at the expected slit positions for our 43 observed sources and found plausible emission lines in eight objects, with only one line detected at $>5\sigma$ significance. The detected emission line is at a wavelength of 1.0343 μm with an integrated signal-to-noise ratio of 7.8 (Fig. 1) and comes from the object designated z8_GND_5296 in our sample (right ascension 12 h 36 min 37.90 s, declination 62° 18′ 8.5″, J2000). On the basis of arguments outlined below (and discussed extensively in the Supplementary Information), we identify this line as the Lyα transition of hydrogen at a line-peak redshift of $z = 7.5078 \pm 0.0004$; this is consistent with our photometric redshift 95% confidence range of $7.3 < z < 8.1$ for z8_GND_5296.

As expected for a galaxy at $z = 7.51$, z8_GND_5296 is undetected in the HST optical bands, including an extremely deep 0.8 μm image (Fig. 2). The galaxy is bright in the HST NIR bands, becoming brighter with increasing wavelength, implying that the Lyman break lies near 1 μm and that the galaxy has a moderately red rest-frame ultraviolet colour. The galaxy is well-detected in both Spitzer/IRAC bands (3.6 μm and 4.5 μm wavelength) and is much brighter at IRAC 4.5 μm than at IRAC 3.6 μm. The strong break at observed 1 μm restricts the observed emission line to be either Lyα at $z = 7.51$ (near the Lyman break) or [O II] 3,726 and 3,729 Å (a doublet) at $z = 1.78$ (near the rest-frame Balmer/4,000 Å break). We investigated these two possibilities by comparing our observed photometry to a suite of stellar population models at both redshifts (Fig. 3). A much better fit to the data is obtained when

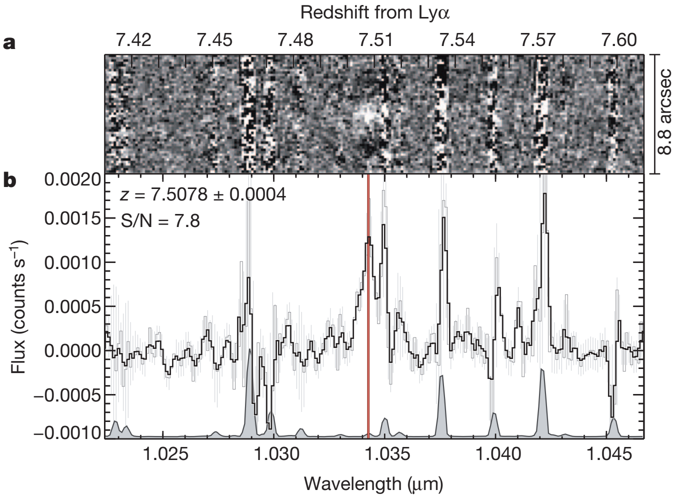

Figure 1 | The observed NIR spectrum of the galaxy z8_GND_5296. **a**, The reduced two-dimensional spectrum. An emission line is clearly seen as a positive signal (white) in the centre, with the negative signals (black) above and below being a result of our 'dithering' pattern in the spatial direction along the slit; this is a pattern only exhibited for real objects. **b**, The extracted one-dimensional spectrum (black, smoothed to the spectral resolution; grey, not smoothed). The sky spectrum is shown as the filled grey curve with the scale reduced greatly compared to that of the data. We measure the line to have a signal-to-noise (S/N) of 7.8, and it is also clearly detected in separate reductions of the first and second halves of the data with signal-to-noise ratios of 6.4 and 5.2, respectively. The line has a full-width at half-maximum (FWHM) of 7.7 Å and is clearly resolved compared to nearby sky emission lines, which have FWHM = 2.7 Å. The red line denotes the peak flux of the detected emission line, which corresponds to a redshifted Lyα line at $z = 7.5078 \pm 0.0004$. All other strongly positive or negative features are subtraction residuals due to strong night sky emission. Although the line appears symmetric, there is a sky line residual just to the red of our detected emission line, which makes a measurement of our line's asymmetry difficult.

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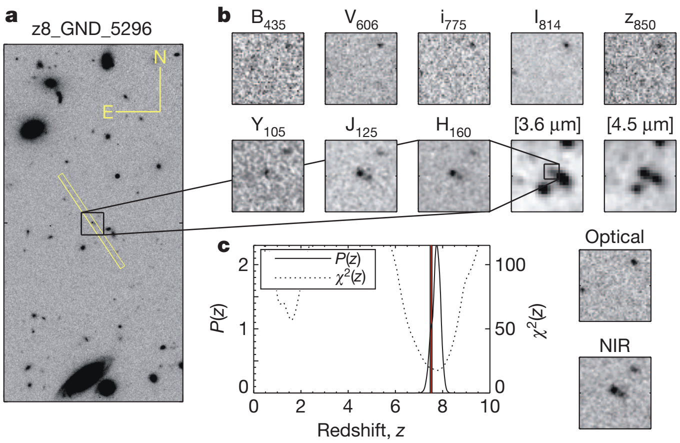

Figure 2 | Images of z8_GND_5296. a, A portion of the CANDELS/GOODS-N field, shown in the F160W filter (centred at 1.6 μm), around z8_GND_5296. CANDELS provides the largest survey volume in the distant Universe deep enough to find $z > 7$ galaxies. The 15″ × 0.7″ slit is shown as the yellow rectangle. **b,** Magnified multi-wavelength images of the boxed area in **a** (around z8_GND_5296); the GOODS and CANDELS HST images (top row, first three images in bottom row) are 3″ on a side, while the S-CANDELS Spitzer/IRAC 3.6 and 4.5 μm images (last two images in bottom row) are 15″on a side. We also show at bottom right mean stacks of the five optical bands and the three NIR bands, the latter showing that this galaxy appears to have a clumpy morphology. This galaxy is not detected in any optical band, even when stacked together, which is strongly suggestive of a redshift greater than 7. The IRAC bands show a faint detection at 3.6 μm and a strong detection at 4.5 μm. This signature is expected if strong [O III] emission is present in the 4.5-μm band, which would be the case for a strongly star-forming galaxy at $z \approx 7.5$ with sub-solar (though still significant) metal content (0.2–0.4 times solar). **c,** The results of our photometric redshift analysis placing z8_GND_5296 at $7.3 < z < 8.1$ at 95% confidence, which encompasses our measured spectroscopic redshift (denoted by the vertical line). We show both the probability distribution function as well as the values of χ^2 at each redshift from the photometric redshift analysis; though a low-redshift solution is possible, it is strongly disfavoured, with the high-redshift solution being $\sim 7 \times 10^9$ times more probable.

using models at $z = 7.51$ than at $z = 1.78$, supporting our identification of the emission line as Lyα. Specifically, the model at $z = 1.78$ would result in greater than 4σ significant flux in the 0.8 μm image as well as a near-zero IRAC colour, neither of which is seen. Additionally, the $z = 1.78$ model requires an ageing stellar population with no active star formation, which would have insignificant [O II] emission. In the Supplementary Information, we discuss a number of tests performed to discern between the Lyα and [O II] hypotheses. In summary, although we cannot robustly measure the line asymmetry owing to the nearby sky residual, the spectral energy distribution (SED) fitting results and the lack of a detected second line in the [O II] doublet lead us to conclude that the detected emission line is Lyα at $z = 7.51$.

This galaxy is very bright in the rest-frame ultraviolet and optical, with an apparent magnitude of $m_{F160W} = 25.6$ and a derived stellar mass of $1.0^{+0.2}_{-0.1} \times 10^9 M_\odot$ ($M_\odot$, solar mass). The blue H – 3.6 μm colour suggests that the moderately red ultraviolet colour ($J - H = 0.1$ mag) is due to dust attenuation rather than the intrinsic red colour of an old stellar population. The presence of dust extinction leads to a higher inferred ultraviolet luminosity. To derive the intrinsic star-formation rate (SFR) for this galaxy, we measured a time-averaged SFR from the best-fitting stellar population models to find SFR = $330^{+710}_{-10}\ M_\odot\ \mathrm{yr}^{-1}$. The very red 3.6 μm − 4.5 μm colour at $z = 7.51$ can only be due to strong [O III] 5,007 Å line emission in the 4.5 μm band; indeed, the SED fitting implies an [O III] 5,007 Å rest-frame equivalent width of 560–640 Å (68% confidence), with a line flux of 5.3×10^{-17} erg s^{-1} cm^{-2}. This very high [O III] equivalent width constrains the abundance of metals in this galaxy, as highly enriched stars do not produce hard-enough ionizing spectra, and very low-metallicity systems do not have

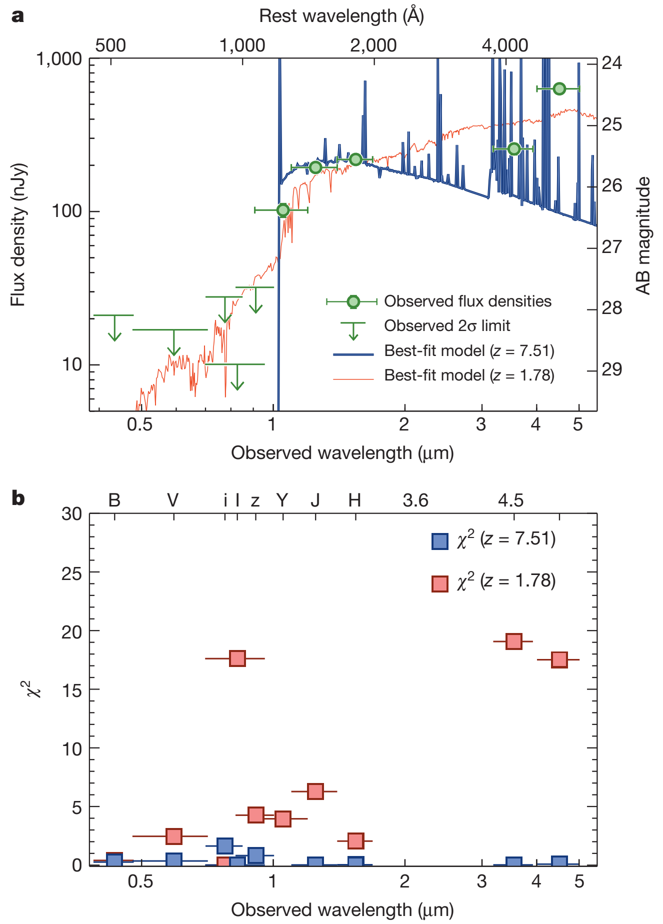

Figure 3 | Spectral energy distribution fitting of z8_GND_5296. a, The results of fitting stellar population models to the observed photometry of z8_GND_5296. The best-fit model for $z = 7.51$ (if the detected emission line is Lyα) is shown by the blue spectrum, while the alternative redshift of $z = 1.78$ (if the line is [O II]) is shown by the red spectrum. The vertical error bars show the 1σ flux errors, while the horizontal error bars (in both panels) denote the bandpass FWHM covered by the filter. **b,** The measured χ^2 for each band for the best-fit model at each redshift. The lack of detectable optical flux, particularly in the deep F814W image, as well as the extremely red IRAC colour, strongly favour the high-redshift solution (reduced $\chi^2[z = 7.51] = 0.8$ versus $\chi^2[z = 1.78] = 14.7$). Additionally, the low-redshift model exhibits no star formation, thus this stellar population should not have detectable [O II] emission. The best-fitting high-redshift model shows that this galaxy has a stellar mass of about $10^9\ M_\odot$, with a 10-Myr-averaged SFR of $\sim 330\ M_\odot\ \mathrm{yr}^{-1}$ (68% confidence limits, 320–1,040 $M_\odot\ \mathrm{yr}^{-1}$). The large SFR may be responsible for the ability of Lyα to escape this galaxy.

enough oxygen to produce strong emission lines. Of the metallicities available in our models (0.02, 0.2, 0.4 and 1.0 times solar), only models with a metal abundance of about 20–40% of solar have [O III] equivalent widths >300 Å. Thus, even at such early times, a moderately chemically enriched galaxy could form. However, because of the discreteness of the model metallicities, further analysis is needed to draw more quantitative conclusions about the metallicity—particularly its lower limit. We note that at $z = 7.51$ [O II] is in the 3.6 μm band, but it is predicted to be about five times fainter than [O III] and thus does not significantly affect the 3.6 μm flux.

The galaxy z8_GND_5296 is forming stars at a very high rate, with a 'mass-doubling' time of at most 4 Myr. The most recent estimates[17] at $z \approx 7$ find that galaxies with stellar masses of $5 \times 10^9\ M_\odot$ typically have specific SFRs (that is, SFR divided by stellar mass) of $\sim 10^{-8}$ yr^{-1}. This galaxy is a factor of five less massive, yet its specific SFR is a factor of 30 greater at 3×10^{-7} yr^{-1}, implying that z8_GND_5296 is undergoing a significant starburst. Additionally, estimates of the SFR functions[9] show

Table 1 | Lyα spectroscopically confirmed galaxies at $z > 7$

ID*	$z_{Ly\alpha}$	M_{UV}† (mag)	Rest equiv. width of Lyα (Å)	SFR‡ ($M_\odot$ yr^{-1})	log[Stellar mass ($M_\odot$)]
z8_GND_5296	7.508	−21.2	8	330	9.0
SXDF-NB1006-2 (ref. 4)	7.215	−22.4§	15	56§	NA
GN 108036 (ref. 3)	7.213	−21.8	33	100	8.8
BDF-3299 (ref. 1)	7.109	−20.6	50	9	NA
A1703_zD6 (ref. 2)	7.045	−19.4	65	4	NA
BDF-521 (ref. 1)	7.008	−20.6	64	9	NA
IOK-1 (refs 3, 6)	6.965	−21.6	43	10	NA
HFLS3 (ref. 26)	6.337	NA	NA	2,900	10.6

NA, not available in the literature.
* Currently known galaxies with $z_{Ly\alpha} > 7$. We include IOK-1 for comparison, as it was the highest-redshift spectroscopically confirmed galaxy for several years, and HFLS3, which has the most extreme SFR known, and may represent the $z \approx 6$ evolution of z8_GND_5296.
† We compute ultraviolet absolute magnitudes (M_{UV}) for BDF-3299 and BDF-512 using the Lyα-corrected Y-band magnitudes, and for A1703_zD6 using the de-lensed J-band magnitude.
‡ The SFR for z8_GND_5296 and GN 108036 were both calculated via SED fitting. The SFR for IOK-1 was measured from Lyα emission, which is likely to be a lower limit, owing to unknown absorption. The SFRs for BDF-3299, BDF-521, A1703_zD6 and SXDF-NB1006-2 were calculated from the ultraviolet luminosity, which are also likely to be lower limits, as the ultraviolet luminosity was not corrected for dust attenuation, and the scaling relation was defined for a stellar population with an age of 100 Myr (ref. 27). The SFR for HFLS3 was derived via the infrared luminosity.
§ SXDF-NB1006-2 was only photometrically detected in a narrow band which encompassed Lyα emission. The corresponding ultraviolet absolute magnitude, and subsequent SFR, are thus highly uncertain, with published uncertainties of $M_{UV} = -22.4^{+\infty}_{-0.4}$(ref. 4).

that a typical galaxy at $z \approx 7$ has SFR $= 10\, M_\odot$ yr^{-1}; the measured SFR of z8_GND_5296 is a factor of more than 30 times greater. If this SFR function is accurate, the expected space density per co-moving Mpc^3 for this galaxy would be $\ll 10^{-5}$. The implied rarity of this galaxy could indicate that it is the progenitor of some of the most massive systems in the high-redshift Universe. However, the $z = 7.213$ galaxy GN 108036 (ref. 3), also in the GOODS-North field, also has an implied SFR $> 100\, M_\odot$. Although the current statistics are poor, the presence of these two galaxies in a relatively small survey area suggests that the abundance of galaxies with such large SFRs may have previously been underestimated. If the high SFR of z8_GND_5296 continues down to $z = 6.3$, it would have a stellar mass of $\sim 5 \times 10^{10}\, M_\odot$, comparable to the extreme star forming $z = 6.34$ galaxy HFLS3 (Table 1)[18]. Should z8_GND_5296 in fact be a progenitor of such submillimetre galaxies, it is probably in the process of enshrouding itself in dust.

Both z8_GND_5296 and GN 108036 also have young inferred ages and IRAC colours indicative of strong [O III] emission. Given the difficulty of detecting Lyα emission at $z \geq 6.5$, it is interesting that these highest-redshift Lyα-detected galaxies appear to have extreme SFRs and high [O III] emission. It may be that a high SFR and/or a high excitation are necessary conditions for Lyα escape in the distant Universe—perhaps through blowing holes in the interstellar medium (ISM), allowing both Lyα and ionizing photons to escape. An outflow in the ISM of 200–300 km s^{-1} could clear a hole in this galaxy in about 3–5 Myr, or perhaps even sooner if the galaxy is undergoing a merger, which could preferentially clear some lines of sight for Lyα to escape.

Finally, we examine the lack of detected Lyα lines in our full data set. If the Lyα equivalent width distribution continues its observed increase[19] from $3 < z < 6$ out to $z \approx 7$–8, we should have detected Lyα emission from six galaxies. Our single detection rules out this equivalent width distribution at 2.5σ significance. This confirms previous results at $z \approx 6.5$ (refs 3, 5, 6 and 8), but here we probe $z > 7$. The lack of detectable Lyα emission is unlikely to be due to sample contamination, as contamination by lower-redshift interlopers is probably not dominant at $z = 7$ given the low contamination rate at $z = 6$ (ref. 8). To explain the low detection rate of Lyα, a neutral fraction in the intergalactic medium (IGM) at $z = 6.5$ as high as 60–90% has been proposed[3,8], implying a rapid increase from $z = 6$ (ref. 20). However, most other observations are consistent with an IGM neutral fraction $\leq$10% at $z = 7$ (refs 21, 22), thus alternative explanations for the dearth of Lyα emission need to be explored.

One alternative explanation for at least part of the Lyα deficit may be gas within galaxies. A high ratio of gas mass to stellar mass may be consistent with the very high SFR of z8_GND_5296, as galaxies should not have SFRs (for long periods) exceeding their average gas accretion rate from the IGM (which is set by the total baryonic mass). For the inferred stellar mass and redshift, z8_GND_5296 must have a gas reservoir of about 50 times the stellar mass to give an accretion rate comparable to the SFR[23]. If true, this galaxy would have a gas surface density similar to the most gas-rich galaxies in the local Universe, and its SFR would be consistent with local relations between the gas and SFR surface densities[24]. The large gas-to-stellar mass ratio could be due to low metallicities at earlier times which may initially inhibit star formation, allowing the formation of such a large gas reservoir[25]. If such high gas-to-stellar mass ratios are common amongst $z > 7$ galaxies, it could explain the relative paucity of Lyα emission in our observations. Direct observations of the gas properties of distant galaxies are required to make progress in understanding both the fuelling of star formation and the escape of Lyα photons.

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Supplementary Information is available in the online version of the paper.

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